JOINT PAINT REMOVAL STUDY

JOINT POLICY COORDINATING GROUP ON DEPOT MAINTENANCE

TASKING DIRECTIVE 1-90

FINAL REPORT

ON

CARBON DIOXIDE PELLET BLASTING

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June 1995

FOREWORD

This is the final report for the carbon dioxide (dry ice pellets) paint stripping process, validation, and optimization. This is one of five individual studies directed by the Joint Policy Coordinating Group on Depot Maintenance, Tasking Directive 1-90 (Appendix I).

This program evaluated paint stripping based on carbon dioxide pellet blasting. The validation efforts described herein were performed by the U.S. Air Force and U.S. Navy, at air logistics centers and shipyards. The Air Force's goal was to refine the paint stripping process for optimum performance and to qualify it for Air Force use. The Navy evaluated the process for removal of marine growth from clad areas on submarine main seawater hull and backup valve cavities.

Points of contact for the Joint Paint Removal Study are in Appendix III.

EXECUTIVE SUMMARY

BACKGROUND:

The Joint Policy Coordinating Group on Depot Maintenance (JPCG-DM) tasked the Joint Technology Exchange Group (JTEG) to study alternative paint removal processes that have potential use within the Department of Defense depot maintenance community. The JPCG-DM signed Tasking Directive 1-90 on 19 Dec 89 (Appendix I) and directed the JTEG to plan and manage the study. This included identifying techniques to be studied, sponsoring and advocating research and development initiatives, overseeing joint Service testing, evaluating the study, and reporting the results.

OBJECTIVE:

The objective of the study is to give coordinated joint Service technical and management information to help managers make investment and application decisions regarding current and emerging paint removal processes. The study will identify and evaluate alternative paint removal processes and help managers eliminate redundant developmental efforts.

SCOPE:

To realize the quickest benefits, the JTEG studied only the five most prominent alternative being developed to replace chemical paint stripping: plastic media blasting, laser, sodium bicarbonate blasting, carbon dioxide pellet blasting, and high pressure water blasting. To reduce costs and time frames, tests were conducted at facilities that had already established or begun efforts to establish organic capability.

STUDY PLAN: The study consisted of three phases.

Phase I was a comprehensive review within DOD to identify existing capabilities/plans and to establish a baseline for the study. The baseline, which related to the five alternatives, identified current capabilities, the degree of maturity for each method, developmental efforts and time frames, and study criteria. Also, from the baseline data, lead activities were recommended and study teams established.

Phase II covers the feasibility study, testing, and analysis, which began when the JTEG designated lead activities and developed a coordinated plan for each process to include economic, environmental, and technical evaluations. During Phase II, the status of each alternative process was reported periodically to the JPCG-DM and the depot maintenance community.

Phase III involves analyzing and documenting the processes. As each process is tested an interim report will be provided. When studies are complete, a final report will be published and disseminated within the DOD.

SUMMARY FOR CARBON DIOXIDE PELLET BLASTING

The carbon dioxide (CO_2) blast system is environmentally desirable since the CO_2 (dry ice) pellets sublime after blasting and the removed coating is all that's left for disposal. Primarily, stripping is accomplished as an abrasive blast process. However, stripping/cleaning is also attributed to the physical shock of impact and the thermal shock of the dry ice pellets. The Air Force's purpose for its project was to refine the process for optimum performance and to qualify it for use. Naval Sea Systems Command asked Norfolk Naval Shipyard to evaluate the process for shipyard applications and to compare the performance of two manufacturers' equipment. Pearl Harbor Naval Shipyard evaluated CO_2 blasting because of the potential for replacing hydroblasting and hand cleaning of main and auxiliary sea water hull and backup valve parts, cavities, and sea chests.

The Air Force assembled a CO_2 blast system at Oklahoma City Air Logistics Center (OC-ALC) to incorporate and evaluate process improvements necessary to identify and develop a useful, production-ready paint stripping process. After exploring all available process parameters without success, the Air Force concluded it could not achieve a usable stand-alone process. Inconsistency, slow strip rates, and excessive substrate damage plagued the process.

Testing at OC-ALC evolved into efforts to augment the basic CO_2 process with environmentally acceptable chemical softeners, supplemental heat, and/or liquid nitrogen refrigeration. The ALC selected chemical softeners as the most promising near-term technology, and screened and evaluate various softeners. Although efficient stripping was occasionally achieved, the process remained inconsistent and, therefore, unsuited for production aircraft stripping. The ALC eventually discontinued further qualification efforts.

Subsequently, Warner Robins Air Logistics Center (WR-ALC) developed a CO_2 process augmented with liquid nitrogen that was marginally successful. The ALC implemented the process for limited production stripping of F-15 aircraft. Because the process was extremely slow, its use has been discontinued.

Norfolk Naval Shipyard compared two manufacturers' equipment to provide enough data to allow the Navy's shipyards to select the best CO_2 blasting system on a firm technical basis. Previous testing and experience had identified the most important parameters for the test. The shipyard compared processing rate, operating cost, ease of use, impact on base material, and the equipment’s ability to improve productivity.

Pearl Harbor Naval Shipyard evaluated CO_2 pellet blasting for its effectiveness and efficiencies with the specific objective of replacing some of the shipyard's hand cleaning, abrasive grit blasting, and solvent cleaning processes. Pearl Harbor obtained excellent results in removing marine growth and soft, fluid films such as grease and oil. Concerns about the harmful effects of temperature changes in substrata material were dispelled as the shipyard determined that the "thermal shock" is confined to a thin surface layer. Its cost analysis show potential savings and intangible benefits in the ability to complete work sooner with less interference with other work schedules.

Although the shortcomings of the CO_2 process use on aircraft are well known, other facility and weapons support equipment may be cleaned and stripped effectively due to their substrate thickness and paint system. NADEP Jacksonville, Naval Air Systems Command's lead maintenance technology center for the environment, has borrowed a CO_2 pellet blaster from WR-ALC to develop, test, and evaluate alternative uses. For example, NADEP Jacksonville is evaluating a synergistic process of xenon flash lamp and CO_2 pellet blasting for aircraft paint stripping. The NADEP also is evaluating the use of CO_2 snow where the gas is not pressed into pellets but formed into a low-density snow/gas mixture that gently flushes sensitive surfaces of contaminants and soils. The CO_2 snow process may replace current processes that use ozone layer depleting substances to clean sensitive aircraft exteriors, electronic access areas, hydraulic system areas, and avionics boards, boxes, and connectors.

McDonnell Douglas, Corp. has developed a successful hybrid process based upon flash lamp technology. The process uses CO_2 in a secondary mode, for cleaning up charred paint residue instead of using it as the primary paint removal tool.

TABLE OF CONTENTS

SECTION I - OVERVIEW OF CARBON DIOXIDE (CO_2) PELLET BLASTING

1.1 INTRODUCTION

1.1.1 Traditionally, paint has been removed from the surfaces of aircraft using methylene chloride/phenol chemical stripper. This material is suspected of being carcinogenic and it releases volatile organic compounds into the environment. The Occupational Health and Safety Administration (OSHA) and the Environmental Protection Agency (EPA) are concerned about the hazards and advocate discontinuing its use in the near future. Therefore, the aircraft industry is searching for non-hazardous, environmentally acceptable, alternative paint removal methods. Carbon dioxide (dry ice) pellet blasting is a potential that has been used for cleaning purposes for several years. However, its paint stripping ability has been limited to removing residue following chemical stripping. Cold Jet Inc. has developed an improved pelletizing capability and specialized nozzles that have increased the aggressiveness of the process. These developments have fostered a need to evaluate carbon dioxide (CO_2) blasting for its potential as a stand-alone paint removal method.

1.1.2 Cold Jet, Inc. demonstrated the capability during the fall of 1989 at the Aerospace Museum in Oshkosh, WI, by fully stripping a DC-3 aircraft that was being prepared for restoration and display. The DC-3 aircraft's paint system was not identified and not entirely representative of present military paint systems. However, the demonstration was impressive and, therefore, warranted further development and evaluation is warranted.

1.1.3 The Air Force funded a project to fully evaluate paint removal from military aircraft using the CO_2 blast process. HQ Air Force Material Command funded for hardware and contracted technical support by Battelle, Columbus. Test facilities and personnel were provided by the Oklahoma City Air Logistics Center's (OC-ALC) Engineering Test Laboratory. From the outset the Air Force recognized that the process was an immature technology. Therefore, a close working relationship was established with the equipment vendor, Cold Jet, Inc. In this manner, equipment modifications could be readily identified, developed, and evaluated to support the ultimate objective of producing a production ready aircraft paint removal process.

1.1.4 The Navy funded projects were funded to evaluate CO_2 blasting for its potential to eliminate the use of hazardous materials in the production process. Also, the Navy identified CO_2 blasting as an alternate technology for cleaning the main, seawater hull and backup valves on submarines. The labor intensive and time consuming hydroblast process in use at Pearl Harbor Naval Shipyard leaves a film that requires follow-up hand cleaning. After leasing a CO_2 blasting machine and air compressor for 30 days the shipyard's industrial engineers proposed the CO_2 blast process to reduce hand-cleaning requirements by at least 90 percent.

1.2 GENERAL DESCRIPTION OF CARBON DIOXIDE PELLET BLASTING

1.2.1 Carbon dioxide blasting offers inherent environmental and potential economic advantages over other paint stripping alternatives. CO_2 is a nontoxic, nonflammable, naturally occurring gas that may be bought and stored on-site in liquid form. Commercially available liquefied CO_2 is a by-product of other industries where it would normally be released to the atmosphere. Capturing and liquefying the gas allows recycling for other useful applications (such as paint removal) before its release. Thus, CO_2 paint removal does not contribute to atmospheric pollution.

1.2.2 The cost of the liquid CO_2 is approximately \$.06 per pound delivered on-site where it is converted into a pellet form for use as a blast media. Equipment for making pellets allows the highly compressed and refrigerated liquid to flash into an approximate 50/50 mixture of gas and dry ice snow. The equipment subsequently compressed and extruded the snow through a precision die plate into pellet form suitable for blasting (\$.12 per pound).

1.2.3 In the Cold Jet, Inc., system, the die plate configuration controls both the density and size of the pellets. Thus, operators can adjust the performance characteristics of the blast media by changing the die plate. The extrusion process produces pellets of constant diameter but with a random length ranging from 0.125 to over 0.5 inch. The process produces pellets upon demand up to the maximum capacity of the equipment. A small temporary storage hopper provides several minutes of blast time to allow the system to respond to start-stop operations. The hopper supplies pellets to a variable rate positive displacement feed mechanism. The feeder allows the operator to precisely control the media mass flow rate and mixes media into the blast air stream.

1.2.4 An external source of compressed air propels the media through the feed hose to a converging/diverging nozzle where the operator directs it toward the work piece. The media approaches sonic velocity and disintegrates upon impact with the work piece. The fractured pellet almost instantly sublimes into harmless gas, leaving paint chips as the only residue that requires disposal.

1.2.5 The process' compatibility with any dry, well-ventilated facility contributes to low implementation cost by allowing use of existing facilities. Operating cost for electrical energy and media is moderate compared to alternative processes, however, the economy of the process for manual operation is contingent upon paint strip rate and its effect on labor cost.

1.3 BLASTING EQUIPMENT

1.3.1 The Air Force and Pearl Harbor Naval Shipyard selected Cold Jet, Inc., blast units for use in evaluating the CO_2 process. The model 65/150 series has two pelletizers operating from one set of input equipment and feeding one set of output equipment. With the equipment, OC-ALC purchased die plates that could provide pellet sizes of 0.140, 0.160, and 0.180 inches in diameter. For each size pellet, densities of 85, 90, and 95 pounds per cubic foot could be produced. All together, nine pellet types were available for evaluation. The Cold Jet system, with its auxiliary equipment, consists of the eleven major sub systems illustrated in the following diagram.

General Arrangement

1.3.2 Of the three known manufacturers of CO_2 blast equipment, Cold Jet, Inc., Alpheus Cleaning Technologies Corp., and Cryogenisis, Inc., only Cold Jet, Inc. claimed paint stripping capability. The other systems are sold for cleaning purposes. Cold Jet, Inc. offers three models of equipment.

a. Model 65-100 has a single gun, one pelletizer, and one feeder. Pearl Harbor Naval Shipyard evaluated this model.

b. Model 65-200, a two-gun model, essentially is two 65-100 units mounted on a common chassis. This model consists of two independent pelletizers and feeders.

c. Model 65-150 incorporates modifications to model 65-200, making it highly suitable for test purposes. Model 65-150 only supports one gun but is capable of double the normal pellet flow rate. Both pelletizers supply pellets to a common hopper and a single-feed mechanism. This machine provides the ability to duplicate single-gun characteristics of either the model 65-100 or model 65-200, allowing exploration for potential benefits from increased pellet flow rates (-1200 lb/hr). Oklahoma City ALC selected this model for its evaluation. After the ALC's test, the unit could be economically modified to a two-gun model 65-200 configuration.

1.3.3 Alpheus Cleaning Technologies Corp. demonstrated their equipment for Norfolk Naval Shipyard's evaluation and comparison to Cold Jet, Inc., equipment. Alpheus offers a self-contained CO_2 Clean blast mobil unit consisting of:

a. CO_2 clean blast pelletizer/blaster model 250-1

b. 750/250 portable rotary screw air compressor

c. Par 350 portable dryer/after-cooler package

1.3.4 CO_2 blasting technology, as represented by Cold Jet Inc., and Alpheus Cleaning Technologies Corp., consists of the same process, but with different equipment and operating parameters.

1.3.4.1 Following is a list comparing the range of operating parameters:

Parameter	Cold Jet	Alpheus
CO_2 pellets		
Diameter, in., (cm)	0.125-0.438 (0.318-1.112)	0.0625-0.300 (0.159-0.762)
Density, lb/ft^3, (g/cm^3)	98 (1.57)	54 (0.87)
Feed rate, lb/min, (kg/min)	2.75-25 (1.25-11.3)	3.5,7,11,14 (1.6,3.1,5,6.3)
Air compressor pressure, lb/in^2, (kPa)	80-300 (550-2067)	30-300 (207-2067)
Hose length, ft, (m)	10-300 (3.0-91.4)	50,100,200 (15.2,30.4,61.0)
Power		
Voltage	440	480
Amperage	40	13
CO_2 usage, lb/hr, (kg/hr)	0-940* (0-426)	360-1450 (163-658)
Size, L x W x H, In., (cm)	100x48x73 (254x122x185)	72x38x65 (183x97x165)

* For each of two pelletizers on the unit.

1.3.4.2 Other differences in equipment are:

a. Pelletizers. Both companies have proprietary/patented pelletizers. Cold Jet's pelletizer uses a hydraulically operated ram that extrudes the snow through a round die. The machine produces pellets in batches with each stroke of the ram and stores them in a large hopper. Alpheus's system employs two epicyclic 3- to 4-inch (7.6- to 10.1-cm) rollers rotating inside a 10-inch (25.4-cm) cylindrical die. The rollers continuously extrude the snow through holes in the die into an air lock. Because pellets are produced continuously and without hydraulics, the Alpheus non-portable systems do not require storage hoppers. Also, they are smaller, lighter, and seemingly simpler than comparable Cold Jet systems. In addition, the Alpheus system can produce pellets on demand, thus minimizing waste. Portable Alpheus systems use a hopper that holds a sufficient supply of pellets for up to 3.5 hours of continuous blasting.

b. Transporting pellets. A significant difference between the two systems is in the method of transferring pellet and connecting between the main unit and the nozzle. Alpheus has a patented delivery system that uses two hoses to deliver air and pellets to the nozzle (which is both an injector and a nozzle). One hose delivers high-volume/high-pressure air and another hose delivers the pellets. Introducing compressed air at the nozzle/injector tends to decrease sublimation of the pellets in the delivery hose, but increases the temperature of the blasting air. Both units can optionally use air, CO_2 or nitrogen to propel and blast the pellets; however, both used portable air compressors for the Norfolk Naval Shipyard demonstrations.

c. Nozzles. Both companies have a wide variety of available nozzles that provide different spray patterns and offer different wand shapes and lengths. Both companies can provide special application nozzles to customers upon request. The nozzles are not interchangeable between the two companies, because Alpheus nozzles have two hose connections and a wider footprint (width being the smaller footprint dimension). Cold Jet nozzles have a slight maintenance advantage in that they can be changed without tools; slip ring pliers are needed to change Alpheus nozzles (incorporated as a safety feature). Another difference between the two is a fragmenter device used by Alpheus. The device is installed as an option in the inlet side and upstream of the nozzle by partially disassembling the nozzle with an open-end wrench. It is used to break the pellets into fragments that are smaller and rougher shaped than those produced by the pelletizer. Alpheus expects a new fragmenter assembly to be available soon that can be installed without tools. Following is a summary of off-the-shelf nozzles available from both companies:

Types of CO_2 Blasting Equipment Nozzles

SECTION II - TEST PROGRAM DESCRIPTIONS

2.1 AIR FORCE TEST PROCEDURES

2.1.1 The purpose of Air Force testing was to optimize process parameters that would achieve the fastest possible strip rate while maintaining an acceptable level of aircraft substrate damage. To accomplish this a computer-controlled x-y table was used to transport the test specimen into the blast stream while holding the gun in a stationary position. In effect the Air Force used a two-axis robot, manually adjusted the gun position to fix the standoff distance and gun impingement angle for each series of tests. The test setup allowed the operator to repeat and control variation of the following process parameters:

- Gun distance
- Impingement angle
- Pellet size
- Pellet density
- Pellet mass flow rate
- Air blast pressure
- Gun translation velocity width of stripping footprint
- Nozzle design

2.1.2 The computer controller, along with other remote switches, was installed in the test facility control room to allow remote automated testing. To reduce the number of specimens to a manageable quantity, a new test concept was devised. The concept involved moving specimen at sufficiently low translation velocity to assure complete stripping, then accelerating across the length of the specimen to a velocity exceeding the process capability. This concept was possible when using a computer to control the x-y table. In theory, the velocity at which acceptable stripping ceased would identify the optimum strip rate for a given set of process parameters, while using only one test specimen. In practice, the concept worked well. Also, the test identified characteristics that were not anticipated from the CO_2 process. The stripping width was shown to be a characteristic of the gun velocity, and hot spots within the footprint were identified. Before this test, similar process evaluations were either performed manually or with a x-y table to simply improve repeatability.

2.1.3 Computing the strip rate required measuring and documenting strip widths along with the associated traversing velocities. Actual strip rates were subsequently verified using a constant velocity pass. The variable strip rate test worked well with the Cold Jet nozzle due to its short, wide rectangular footprint. The test would not work as effectively with round footprints normally used by other processes.

2.1.4 For screening purposes, substrate damage was evaluated by subjective judgment and measurement of the Almen arc height after four simulated strip cycles. Arc height measurement was based upon "N" strips fabricated from 2024-T3 bare aluminum material. Based on previous evaluations performed using other stripping processes, a goal of less than .003-inch arc-height was used as the criteria for damage acceptability. Final qualification was to be based on more definitive actual fatigue tests and metallurgical examinations. Substrate damage became a moot point due to the inability of the process to provide even a minimally acceptable strip rate.

2.2 NAVY TEST PROCEDURES

2.2.1 Norfolk Naval Shipyard's evaluation compared the performance of blasting systems manufactured by Cold Jet, Inc., and Alpheus Cleaning Technologies Corp. on a variety of potential shipyard applications. The evaluation was a one-day "snapshot" of each system's performance and was not expected to accurately assess the reliability or maintainability of either system.

2.2.1.1 The demonstrations were best-effort attempts by each manufacturer to clean and remove coatings from a variety of samples. The shipyard gave each manufacturer identical samples, and the manufacturer's representative identified the best setup for each sample (nozzle type, pressures, temperatures, flow rates, and pellet characteristics). One person from the shipyard did all the blasting to eliminate any operator influence during the blasting operation.

2.2.1.2 Previous tests and experience had identified the most important parameters that the shipyard wanted to compare. Blasting on each sample was videotaped and data was collected that characterizes each system's effectiveness, measures removal rates, and determines the damage, if applicable, to the substrates.

2.2.2 Pearl Harbor Naval Shipyard's test of CO_2 pellet blasting was in response to an identified need. Labor-intensive hydroblasting and follow-up hand cleaning were used to remove marine growth from the main seawater hull and backup valves of submarines. Industrial Engineering at Pearl Harbor Naval Shipyard had identified the CO_2 process as a potential replacement that would decrease the hand cleaning requirement by as much as 90 percent and would benefit the shipyard's hazardous waste minimization goals. Grit blasting and chemical cleaning are not suitable alternatives. They had been rejected for cleaning the valves because of the valves' sensitivity to physical and chemical contaminants. Hand cleaning with soft brushes and scrubbing pads had been continued as the only acceptable method.

2.2.2.1 The shipyard leased a CO_2 blasting machine and air compressor Cold Jet, Inc., for a 30 day. The proposal for the equipment was to clean the main sea water hull and backup valves first and then, with the time remaining on the lease and the materials, to clean other items that could benefit from the process. The following is the equipment setup for the evaluation:

- Quincy model 350 compressor (300 cfm at 250 psi) with after-cooler.
- Cold Jet pelletizer and blasting unit, model 100/65 with air drier.
- 150 feet (1.5-inch inside diameter) blasting hose.
- Standard blasting gun with interchangeable nozzles:
    - very high-velocity nozzle (approximately 2000 feet/sec)
    - high-velocity nozzle (approximately 1500 feet/sec)
    - medium-velocity nozzle (approximately 1000 feet/sec)
- Six-ton liquid CO_2 tank.
- Shipyard utilities: electrical - 250 amps, 460 vac, 3 phase.

2.2.2.2 The shipyard initially blasted components in an enclosure in the dry dock, near the valves and hull cut-through. Removable valve components were moved to the enclosure to determine their suitability for CO_2 blasting. Parts blasted in this enclosure were inspected before they were rigged out to the dry dock staging area. The enclosure measured 20 X 20 X 12 ft high and was covered with herculite. The side opposite the door had a 2-ton hoist, plywood flooring, and a 4-ft high wall installed. Openings were cut in the overhead and walls, and a fan provided ventilation.

2.2.2.3 The valve body openings were blanked off with plywood and the sea chest and valve housing were blasted from outside the hull. After the sea chest and all areas reachable from the outside of the valve body had been cleaned, an exhaust fan was connected to the hull opening. Then blasting was performed on the inside, one side at a time, as the blanked openings were uncovered.

2.2.2.4 Pearl Harbor Naval Shipyard planned to establish a process implementation team to identify the functional areas where project support would be required and the specific tasks and areas for testing the CO_2 process for suitability. Team members would initiate appropriate action to implement the process in their areas. Suggested team members were from the Occupational Safety and Health Office, Planning and Estimating, Design (technical specifications), and the Quality Assurance Office (inspection requirements). Representatives from other shops would be invited on a rotating basis to help the team in their respective areas of expertise. The blasting process would be advertised to all production codes and shops for their input during the test period. This approach allows input from the various trades and crafts within the shipyard and reduces administrative overhead and coordination problems normally experienced with such an undertaking.

SECTION III - AIR FORCE EVALUATION (OKLAHOMA CITY AIR LOGISTICS CENTER)

3.1 PROCESS OPTIMIZATION (STAND-ALONE CARBON DIOXIDE)

3.1.1 For a quick look at the process for use on military paint and to gain insight as to the effects of each process parameter, OC-ALC did initial tests replicating the Oshkosh demonstration settings. Using these initial parameters, the ALC made minor variations to blast pressure, mass flow rate, and gun impingement angles as indicated in Appendix II, Table 1. No useful stripping was achieved on alclad material. Results show that the paint stripped from the DC-3 at Oshkosh was not representative of current military paint.

3.1.2 A "blind" matrix was performed using coarse iterations on all available parameters and the most aggressive "paint strip" nozzle. This matrix was performed on clad 2024-T3 material painted with MIL-P-23377 class 1 primer and MIL-C-23827 polyurethane paint. The matrix was iterated over the full range of each process parameter in broad steps and on all other parameters with no immediate effort to fine-tune the process. In this manner, the ALC systematically explored all possible combinations of process variables to make sure no potentially useful combination would be overlooked. Test results subsequently were evaluated both subjectively and by multiple linear regression analysis. No useful stripping process was observed, and regression analysis failed to identify trends indicating a potential for increased performance. Test results are in Appendix II, Table 2.

3.1.3 The best process found for each available pellet die plate is summarized in Appendix II, Table 3. The maximum strip rate achieved was 0.04 square foot per minute, with an Almen arc height of 0.003 inch. The low Almen arc height, which later was found to be misleading, will be discussed later.

3.2 PROCESS OPTIMIZATION (CO_2/CHEMICAL SOFTENERS)

3.2.1 Failure to achieve a useful stand-alone CO_2 process caused further efforts to focus on various means of augmentation to increase the strip rate. New, "environmentally safe" chemicals, to soften paint before mechanical removal, had been demonstrated by Lufthansa German Airline with its Aquastrip process. Turco Products, Inc. and Ardrox, Inc., manufacturers of softeners used with Aquastrip, were contacted and a joint development effort began to refine products for use with CO_2.

3.2.2 Screening tests were performed on prototype softeners using all standard military paint systems. The underlying goal was a single product capable of softening all paint systems. However, using a different softener for each paint system also would be acceptable. Initial results were excellent, with strip rates from 1 to 3 square feet per minute indicated.

3.2.3 The increased strip rate identified a previously unknown problem with the CO_2 process, extensive damage similar to hailstone. The increased strip rate provided by the softeners spread the damage on the surface. This showed the problem to be from something other than the basic process. The "hailstone" damage was superimposed on top of an underlying non-damaging process. Severe denting was observed on 0.032-inch thick material even though the Almen arc height was acceptable. Experiments showed that by using the cleaning nozzle instead of the paint strip nozzle most dents were eliminated. Thoughts were that pellets coalescing in the delivery hose resulted in a large mass that dented thin metal on impact. The narrow (.080) exit slot of the cleaning nozzle effectively broke up these large particles before impact. The larger exit (0.120) of the paint strip nozzle allowed these large masses of particles to exit intact, resulting in damage.

3.2.4 Regardless of the actual cause of denting, the cleaning nozzle appeared to eliminate the problem, but the ALC had to repeat the "blind" matrix to establish optimum parameters for the cleaning nozzle. The two smallest low-density pellets, which previously had been shown non-productive with the paint strip nozzle, were omitted during this series of tests. Also, the ALC did not use the medium and high densities with large diameter pellets to minimize substrate damage. Test results for the abbreviated matrix are in Appendix II, Table 4.

3.2.5 A summary of the best parameters for each die plate is in Appendix II, Table 5. Results show a slight loss in stripping performance (0.03 square feet per minute) compared to the paint strip nozzle, but the cleaning nozzle substantially reduced substrate damage.

3.2.6 Evaluation and continued development of the CO_2/softener process revealed several new problems.

a. The performance of softeners was variable from day-to-day even when used on the same part.

b. When the softeners worked effectively, the CO_2 process was not needed. When softening was marginal, the CO_2 process was often unable to provide full stripping on the first pass, and the resulting freezing/drying caused the paint to re-harden. Hardening made subsequent removal impossible and made reapplication of softener necessary. The result was excessive dwell time for multiple applications of softener.

c. Minor denting of thin panels would occasionally reoccur even when using the cleaning nozzle.

3.2.7 Overall, there appeared to be a basic incompatibility between the water-based softeners and the dry, cold CO_2 process, which precluded consistent performance. Efforts to develop the process eventually were discontinued in favor of a stand-alone environmentally acceptable chemical process. These efforts contributed to implementing a safe chemical process at OC-ALC in 1992 for stripping polysulfide-primed aircraft.

3.3 HOT AIR AUGMENTATION

3.3.1 Initial evaluation of the CO_2 process and the observation of frost forming on the surface indicated thermal effects could contribute significantly to the stripping action. Conceptually, each of three different thermal effects could influence the process.

a. First, the chilling effect of the process would embrittle the paint, making it susceptible to removal by mechanical chipping.

b. Second, through the thickness cooling of the paint and substrate would develop shear stress at the paint/metal interface due to different coefficients of thermal expansion, which could further contribute to paint removal.

c. Finally, high-velocity pellet impact with the painted surface would result in high compressive pressure between the pellet and substrate, which could melt the pellet. Once the pellet lost its kinetic energy, the liquefied CO_2 would flash and refrigerate the surface. Thoughts were that substrate heating, coupled with this surface refrigeration of the paint, could tremendously increase shear stress between the paint/metal interface. Observation showed normal, steady state stripping resulted in through-the-thickness cooling and a loss of the potential temperature difference (and shear stress) between the paint and substrate.

3.3.2 To enhance thermal aspects of the process and possibly increase strip rates, heated compressed air (300^o F) was supplied to the system in an effort to warm the substrate. Instrumented panels were used to measure the temperature on the back of the substrate while using heated air to compare with temperatures resulting from use of ambient temperature air. Surprisingly, the substrate temperature actually decreased significantly (-40^o F) when using hot air. However, no change was observed in the strip rate. The reason for the phenomena is unknown.

3.3.3 In an additional effort to capitalize on increased thermal gradient, heated air was injected into the blast stream immediately upstream of the blast nozzle. This achieved the desired goal of increasing substrate temperature but, again, had no measurable effect on the strip rate.

3.3.4 Next the ALC tested the process using 10 times the normal strip velocity and making multiple passes (10 each) while observing the stripping. The test panel was allowed to return to the ambient temperature between each pass. In effect, this increased the number of thermal cycles by a factor of 10 while keeping the accumulated abrasion constant. Stripping remained constant as a function of abrasion. These tests led the ALC to conclude that CO_2 stripping is primarily an abrasive process, and thermal effects are incidental.

3.4 EQUIPMENT PERFORMANCE OBSERVATIONS

3.4.1 Cold Jet equipment functioned throughout the test without mechanical deterioration. However, several undesirable traits influenced the systems total performance.

a. The equipment does not lend itself to intermittent operation. Pellet production is inefficient and pellet properties are inferior during the first 15-30 minutes of operation. A cool-down period is required before efficient pellet production occurs. During this cool-down period, pellets must be discarded.

b. Following the cool-down procedure, short periods of idle time (5-10 minutes) result in pellet deterioration in the hopper and, again, pellets need to be discarded.

c. Pellets tend to conglomerate into a solid mass during storage, preventing pellet flow from the hopper to the feed mechanism. This characteristic may have been aggravated by the design of the large hopper used in the model 65-150 and may not occur in other units.

d. Lengthy idle time also can result in internal freezing of the pelletizer, completely locking up the hydraulic ram. Correcting the problem requires either disassembling the pelletizer to remove compacted snow or simply allowing the unit to thaw overnight before resuming operation. Both solutions need extensive equipment down time.

e. Although the pelletizer worked well during continuous blasting, atmospheric moisture condensed and froze on the outside of the blast nozzle. Resulting ice buildup at the nozzle exit disrupts pellet flow and degrades blast performance. Periodic ice removal, best achieved by banging the nozzle against a hard surface, is frequently required. This buildup is only a nuisance for manual stripping, but would be intolerable for CO_2 stripping with robotics. Efforts to curtail ice buildup, including Teflon shielding, failed to eliminate the problem.

3.4.2 Sound in excess of 120 db was measured at the gun. At this sound level, double hearing protection is required for operators and nearby workers. Even with double protection, workers' exposure should be limited to two hours maximum during any 24-hour period. This limitation poses a severe handicap for manual production.

3.4.3 Static electricity generated at the nozzle requires grounding both the aircraft and the gun. On one occasion, a continuous 2-inch arc was observed. Such potential for static discharge dictates de-fueling and purging the aircraft before stripping.

3.5 CONCLUSIONS/RECOMMENDATIONS

3.5.1 In its present form the CO_2 process is not suitable for aircraft paint removal. Process economy is controlled primarily by labor costs that are directly associated with strip rate. A tenfold increase in strip rate is necessary to make the process economically viable.

3.5.2 The CO_2 process primarily is an abrasive blast process, and future development efforts should focus on increasing the pellet quality as a means of increasing the strip rate and reducing total operating cost.

3.5.3 The process was incompatible with water-based chemical softeners as a means of increasing the strip rate.

3.5.4 Ergonomic improvements are needed to eliminate the noise hazard and to reduce the weight and thrust of the gun.

3.5.5 Modification of the pelletizer is needed to allow intermittent operation without malfunction.

3.5.6 The basic process appears to be relatively non-damaging to aircraft substrates. All potential for hailstone-type damage must be eliminated.

3.5.7 Although the process has potential, because of its economical and environmental desirability, further qualification tests are not recommended until the issues listed above have been corrected and demonstrated.

SECTION IV - NAVY EVALUATION

4.1 NORFOLK NAVAL SHIPYARD EVALUATION

4.1.1 The Norfolk Naval Shipyard compared the equipment performance of Cold Jet, Inc., to that of Alpheus Cleaning Technologies Corp. Each manufacturer received identical samples that required surface preparation. Norfolk NSY selected the samples to provide a cross section of potential CO_2 applications on the shipyard. They included a variety of base materials, primers, surface coatings, and surface contaminants. Following is a list of the comparative test samples.

Sample	Base material	Materials to be removed
1. Radome	Fiber Glass	Primer and enamel
2. Antenna array reflector	Fiber Glass	Epoxy
3. Linear wave guide	Fiber Glass	Epoxy
4. Hatch cover	Fiber Glass	Epoxy
5. Fairing strip	Composite	Epoxy
6. Antenna array reflector, SPS10	Aluminum	Epoxy
7. Antenna array reflector, AS-2188	Aluminum	Epoxy
8. Metal plate	Aluminum (smooth)	Epoxy (two coats)
9. Metal plate	Aluminum with profile	Enamel (1st pass) leaving Epoxy primer (2nd pass)
10. Fairing strip	Aluminum	Plastic coating
11. Tube	Aluminum	Plastic coating
12. Metal plate	Steel	Enamel (1st pass) leaving Epoxy primer (2nd pass)
13. Metal plate	Steel profile	Epoxy (two coats)
14. Large tile	Rubber	Epoxy
15. Small special hull treatment (SHT) tile	Rubber	AF paint
16. Stern tube, fairwater, rope guard	Steel	Copper-vinyl (1st pass) AF paint (2nd pass) lv Epoxy primer (3rd pass)
17. Catapult cover	Stainless steel	Grease and Carbon
18. Cable	Steel	Grease covering
19. Sounding horn	Aluminum	Corrosion inside

4.1.2 Evaluation Results.

4.1.2.1 Fiber Glass. Neither Cold Jet nor Alpheus removed coatings from fiberglass satisfactorily. While it was not readily noticeable by visual inspection, blasting caused some degree of delamination or damage to the fiberglass samples (samples 1 through 3) in areas where the gel coat was thinnest. The hatch covers (sample 4) were not evaluated because they had been patched previously and the gel coat was chipped and cracked.

4.1.2.2 Epoxy Coatings. The removal rate of the epoxy coatings on samples 6, 7, 8, 13, and 14 was prohibitively slow for productive use. In addition, the CO_2 pellets damaged their substrates. The epoxy coating was removed successfully from sample 5 with no damage to the composite material it covered because of the epoxy's smooth and tough surface. Removing the epoxy from metal substrates was very slow as data on samples 9, 12, and 13 illustrate. Generally, epoxy removal is successful only on substrates with smooth surface profiles and those that are not easily damaged.

4.1.2.3 The following is a summary of blasting results for the 11 samples that were processed successfully by one or both of the CO_2 blasting systems tested. The Alpheus blaster expended 840 lb/hr (380 kg/hr) during these operations and the Cold Jet unit expended less than 350 lb/hr (159 kg/hr). Usage per square foot for the two units was comparable.

		Cold Jet			Alpheus	
Sample	Air Pressure, lb/in^2 (kPa)	CO_2 usage lb/ft^2 (kg/m^2)	Removal rate,* ft^2/hr (m^2/hr)	Air pressure, lb/in^2 (kPa)	CO_2 usage lb/ft^2 (kg/m^2)	Removal rate,* ft^2/hr (m^2/hr)
5.	280 (1929)		G	200 (1378)		VG
9.(1st)	285 (1964)	24.0	14 (1.3)	220 (1516)	28.2 (150.0)	30 (2.8)
(2nd)		(117.0)				5.3 (0.49)
10.	250 (1723)	70.2 (342.6)	5 (0.46)	240 (1654)	52.8 (280.2)	16 (1.5)
11.	250 (1723)		G	220 (1516)		VG
12.(1st)	150 (1034	14.4 (70.2)	26 (2.4)	220 (1516)	21.0 (111.6)	40 (3.7)
(2nd)				220 (1516)	168 (858.O)	5 (0.46)
13.	285 (1964)	10,920 (53,280)	0.033 (0.003)	220 (1516)	16,140 (85,680)	0.052 (0.0047)
15.	260 (1791)		G	280 (1929)		VG
16.(1st)	250 (1723)	10.2 (49.8)	34 (3.2)	210 (1447)	10.8 (57.6)	77 (7.2)
(2nd)	150 (1034)	26.4 (129)	13 (1.2)	150 (1034)	17.4 (92.4)	48 (4.5)
(3rd)	80 (551)	13.8 (67.2)	11 (1.0)	90 (620)	22.8 (121.2)	37 (3.4)
17.	250 (1723)	24 (117)	14 (1.3)	240 (1654)	36.6 (194.4)	23 (2.1)
18.	285 (1964)		VG	80 (551)		VG
19.	-		VG	150 (1034)		VG

*Samples that could not produce accurate rate measurements were rated as G for good or VG for very good when compared with current methods used to remove coatings.

4.1.3 Conclusions.

a. CO_2 blasting effectively removes oil and grease.

b. CO_2 blasting effectively removes enamels, antifouling paint and plastic coatings.

c. The Alpheus system demonstrated higher coating removal rates on samples that could be measured.

d. CO_2 blasting is prohibitively slow for production use in removing epoxies from metal substrates.

e. CO_2 blasting successfully removed epoxy from fiberglass but caused some damage and delamination.

f. CO_2 blasting did not remove epoxy paint from aluminum radar equipment without damaging the radar structure.

g. CO_2 blasting will remove antifouling paint without damaging epoxy anticorrosive coatings or special submarine hull tiles (SHT).

4.1.4 Recommendations.

4.1.4.1 Norfolk NSY recommends that use of CO_2 blasting for removing coatings from fiber glass should not be abandoned based totally on its evaluation. The shipyard feels that fairly assessing the procedures will require further tests to address the following issues.

a. Fiberglass parts should be inspected carefully before blasting to make sure they are not already damaged. A nondestructive test should be used to make sure no delamination already exists and that the gel coat is uniform and thick enough.

b. The process parameters should be fine tuned for the specific application and, if damage still occurs, the failure mode, related to temperature or impact, should be determined.

4.1.4.2 The shipyard recommends that potential purchasers of CO_2 blasting equipment contact recent customers of both companies to discuss performance, reliability, and maintainability. Also, users may want to rent the selected system until its performance, reliability, and maintainability can be evaluated fully for their use.

4.2 PEARL HARBOR NAVAL SHIPYARD (PHNSY) EVALUATION

4.2.1 Evaluation of the CO_2 blasting process [main seawater (MSW) and auxiliary sea water (ASW) valves].

4.2.1.1 The CO_2 process excelled in removing marine contaminants. The clad surface was free of all debris and contaminants (squeaky clean to the touch). Initial blasting was a "brush blast" using the wide, medium-velocity nozzle to remove most of the contaminants. This was particularly effective on the sea chest due to easy access. Then, the narrower, high-powered nozzles were used to clean areas with remaining debris. The long highest-powered nozzle was preferred when it could be maneuvered to clean an area.

4.2.1.2 The wide, medium-velocity nozzle was efficient for removing marine growth when the initial blast could be maintained perpendicular to the blast surface. The efficiency decreased rapidly, however, as the impact angle deviated from 90^o. The process works best, therefore, when a hole is punched through the debris coating with a 90^o blast. Then the edges of the hole are attacked at a 70^o- to 80^o-angle with the blast stream acting like a chisel to chip the contaminants. The waste stream could be controlled and directed away from the cleaned area into a catch area for easy cleanup.

4.2.1.3 The process is extremely effective at a 45°- to 60°-angle of attack for removing soft, fluid films, such as grease and oil, from parts. Using an extreme angle permits easy control of the waste stream to avoid contaminating the cleaned area.

4.2.1.4 Concerns about the adverse effects of blasted material cooling during the process were dispelled. Shipyard observations were in line with previous testing and research by the Production Engineering Research Association of Great Britain. Tests show that high-temperature drops of about 60° C are experienced at the surface; however temperature within the substrata, even at depths as little as 0.5 mm from the surface, falls off very slowly. Thus the thermal shock is confined to a thin surface layer.

4.2.1.5 Other than damage from moving the valve parts, the containment area was reusable. Containment used in this manner with grit blasting processes usually is damaged sufficiently to require disposal. The blast pellets disintegrate within about 10 feet of the blast nozzle. A single sheet of herculite is sufficient to contain the blast process and debris.

4.2.1.6 The Occupational Safety and Health (OSH) office monitored the evaluation. The office documented a significant noise hazard (approx. 109 db average) from the blasting gun. Double hearing protection and a posted noise hazard area are required. CO_2 concentrations in the exterior blasting area were considered safe for workers. Air-fed respirators are required in enclosed areas or when OSH procedures specify in relation to the coating being removed. Otherwise, dust mask, eye protection, face shield, gloves, and standard personnel protection equipment are required.

4.2.2 Cost Analysis.

4.2.2.1 Total cost for CO_2 blast trial (by type)

Direct costs		
Labor (224 + 192) mh @ $55.00/mh	22,880	
Material (CO_2) 41,000 lb @ $0.22/lb	9,020	
Lease (full cost, 30 days)		22,000
Total direct		53,900
Indirect costs (estimated)		
Rigger support (3-hr crane service)		525
Temp. service, electrical (8 mhr)		440
Containment (40 mhr)		2,200
Total indirect		3,165
Total cost		57,065

4.2.2.2 Total cost for CO_2 blast trial (by task)

MSW job	Direct	36,646
	Indirect	3,165
ASW job		2,448
Non-productive costs (see para.4.2.2.3 c.)		14,806
Total		57,065

4.2.2.3 Allocation of direct costs

a. MSW hull and backup valves

Labor (376.8 mh @ $55.00)	20,724
CO_2 (34,600 lb @ $0.22)	7,612
Lease (11.3 days @ $733.33/day)	8,310
Total	36,646

b. ASW sea chests

Labor (10 mh @ $55.00)	550
CO_2 (6400 lb @ $0.22)	1,408
Lease (0.7 day @ $733.33/day)	490
Total	2,448

c. Other non-productive expenses

Labor (29.2 mh @ $55.00) *	1,606
Excess lease (12 days @ $733.33/day)**	8,800
Admin. delays (6 days @ $733.33/day)***	4,400
Total	14,806

Total direct cost 53,900

4.2.2.4 Combined direct cost matrix

	Lease	Labor	Material	Job total
MSW	8,310	20,724	7,612	36,646
ASW	490	550	1,408	2,488
Admin.	4,400***	--	--	4,400
Excess	8,800**	1,606*	--	10,406
Type total	22,000	22,880	9,020	53,900

Notes: * The downtime labor charge refers to the labor charged to the job after the blaster had been instructed to request a secondary job assignment. In these cases the blaster was charged to the MSW valve job order for the entire shift.

Date	Shift	Down time Start	Down time Stop	Man Hrs	Reason
6/5	3rd	0210	0730	5.3	Ran out of liquid CO_2
6/8	2nd	1815	2400	5.9	Compressor down
6/8	3rd	2330	0730	8.0	Compressor down
6/12	2nd	2300	2400	1.0	Blaster odd shift, only 7 hrs
6/14	2nd	1530	2000	4.5	Blast machine down
6/15	--	--	--	4.5	Ran out of CO_2
Total				29.2	

** Excess lease cost refers to that portion of the equipment lease cost that was paid by the MSW job order but not actually used to support that job.

*** Admin. costs refer to the lost equipment lease time attributed to admin-related delays, primarily, caused by waiting for support services (transportation, rigging, and electrical connection).

4.2.2.5 Comparing the cost of the old method to the CO_2 process, analysis reveals a net loss of $3,646. Losses are attributed to initial startup costs, learning curves, and higher initial costs for the machine lease plus the cost of CO_2 consumed. Predicted performance for the next MSW job, as the proposed job order allowances to be issued, will reflect net savings of $10,660. Also, intangible benefits exist in the ability to complete the job in approximately 10 days instead of 21 days. This becomes a scheduling advantage for the dry docking stay and reduces the probability of the process interfering with other work.

4.2.3 Other Applications.

4.2.3.1 A test patch of approximately 40 ft^2 of organotin antifoulant paint was removed from the hull of landing craft, mechanized (LCM). The process took 35 minutes and used 220 lbs of CO_2. The cost per square foot is $2 that is significantly less than the cost of using chemical strippers and manual methods. Other blasting methods, hydroblast or wet-grit, do not compare with CO_2 blasting due to the hazardous waste cost/constraints.

4.2.3.2 The shipyard satisfactorily removed ablative coatings from test panels. The process effectively removes ablative coatings from vinyl without damaging the vinyl coat. The removal rate is significantly less than that of grit blasting, but the lack of damage to the substrata is an attribute. An interesting aspect of the process is that damaged areas in vinyl coating are easy to identify after CO_2 blasting. Although the CO_2 process will not remove good vinyl paint, areas with poor adhesion will be exposed and the vinyl coating can easily be removed up to the point where the adhesion is stronger. Several defects in the vinyl coatings on the LCM and the test plates were exposed and cleaned sufficiently to permit the immediate application of new paint. These defects would have been very difficult and time consuming to locate using inspection methods.

4.2.3.3 Lubricants consisting of various greases and oils were blasted from a flat metal plate and a section of gantry crane hoisting cable. The process removed all lubricants very well; it did not leave any film, and it cleaned deep between the strands of the cable. To clean an entire crane hoisting cable with the current method would be too time consuming, but, with a circular blasting gun (donut) that blasts the entire circumference of the cable as it is pulled through, would be cost effective. An automated system may prove cost effective for cleaning and re-lubricating the cable.

4.2.3.4 One of the variable pitch propellers on a ship was cleaned using the CO_2 blasting process and the other, a routine process. The routine process procedure requires sensitive areas to be masked and then hand cleaned because of contamination and damage to the seals and seal surfaces from the grit. The CO_2 process cleaned better without the masking and did not damage the bearings, seals, or seal surfaces. The general appearance was that of a new propeller. By contrast, the surface of the hone blasting is more like a "matte" surface, which is rough to the touch. The disadvantage was that the CO_2 process is four times slower than the honing process.

4.2.3.5 The shipyard used the CO_2 process to remove damaged paint from special hull tiles installed on board a submarine. The process removed the paint without damaging the soft tiles, saved money, needed minimum containment, and the job was performed with the hull in the water.

4.2.3.6 The CO_2 process performs excellently but is too expensive to compete with hydroblasting and grit blasting for applications without special considerations. The cost of additional materials, utilities, and time makes the CO_2 blasting to expensive when there is no hazardous waste involved, no surface sensitivity to contamination, preserving the substrata is not a consideration, etc. A significant advantage with the process is the ability to rapidly move the equipment to the work site, set up, and clean small, confined areas with minimal containment, cleanup costs, substrata damage, and interference with other work.

APPENDIX I

APPENDIX II

TABLES

APPENDIX III

JOINT PAINT REMOVAL STUDY
POINTS OF CONTACT

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